Turk Kardiyol Dern Ars 2019;47(8):680-686 doi: 10.5543/tkda.2019.69776

ORIGINAL ARTICLE

Motion-compensated frame rate up-conversion in carotid ultrasound images using optical flow and manifold learning

Optik akış ve manifold öğrenme yöntemlerini kullanarak karotis ultrason görüntülerinde karotis duvar hareketlerine göre kompanse edilmiş kare hızı dönüşümü

Fereshteh Yousefi Rizi, Ph.D.,[1] Sima Navabian, M.Sc.,[1] Zahra Alizadeh Sani, M.D.[2]

The first and second authors contributed equally.

[1]Department of Biomedical Engineering, Islamic Azad University of South Tehran Branch, Tehran, Iran
[2]Department of Rajaie Cardiovascular Medical and Research Center, Iran University of Medical Sciences, Tehran, Iran

ABSTRACT

Objective: Carotid ultrasonography is a reliable and non-invasive method to evaluate atherosclerosis disease and its complications. B-mode cineloops are widely used to assess the severity of atherosclerosis and its progression; however, tracking rapid wall motions of the carotid artery is still a challenging issue due the low frame rate. The aim of this paper was to present a new hybrid frame rate up-conversion (FRUC) method that accounts for motion based on manifold learning and optical flow.

Methods: In the last decade, manifold learning technique has been used to pseudo-increase the frame rate of carotid ultrasound images, but due to the dependence of this method to the number of recorded cardiac cycles and frames, a new hybrid method based on manifold learning and optical flow was proposed in this paper.

Results: Locally linear embedding (LLE) algorithm was first applied to find the relation between the frames of consecutive cardiac cycles in a low dimensional manifold. Then by applying the optical flow motion estimation algorithm, a motion compensated frame was reconstructed.

Conclusion: Consequently, a cycle with more frames was created to provide a more accurate consideration of carotid wall motion compared to the typical B-mode ultrasound images. The results revealed that our new hybrid method outperforms the pseudo-increasing frame rate scheme based on manifold learning.

ÖZET

Amaç: Karotis ultrasonografisi ateroskleroz hastalığını ve komplikasyonlarını değerlendirmek için güvenilir ve invaziv olmayan bir yöntemdir. B-mod sineluplar aterosklerozun ciddiyetini ve zaman içindeki ilerlemesini değerlendirmek için yaygın olarak kullanılmasına rağmen, karotis arterin hızlı duvar hareketlerini izlemek düşük kare hızı nedeniyle yine de zorlayıcı bir konudur. Bu yazıda, manifold öğrenmeye ve optik akışa dayalı hareketi hesaba katan yeni bir karma yüksek kare hızı dönüştürme (FRUC) yöntemi sunuldu.

Yöntemler: Son on yılda, karotis ultrasonu görüntülerinin kare hızını artırmak için manifold öğrenme tekniği kullanılmış olmasına rağmen bu yöntemin kaydedilen kardiyak siklus ve karelerin sayısına bağlı olması nedeniyle, manifold öğrenmeye ve optik akışa dayalı yeni bir hibrit (karma) yöntem önerilmiştir.

Bulgular: Yerel doğrusal gömme (LLE) algoritması, ilk önce düşük boyutlu bir manifoldda ardışık kardiyak döngülerin kareleri arasındaki ilişkiyi bulmak için uygulandı. Daha sonra, optik akış hareket kestirim algoritması uygulanarak, yeniden duvar hareketlerine göre kompanse edilmiş bir kare oluşturuldu.

Sonuç: Sonuç olarak, tipik B-modu ultrason görüntülerine kıyasla karotis duvar hareketinin daha doğru bir şekilde değerlendirilebilmesi için daha fazla sayıda kare içeren bir siklus oluşturulmuştur. Sonuçlar, yeni hibrid yöntemimizin manifold öğrenmeye dayalı artırılmış kare oranı şemasına göre daha iyi bir performans gösterdiğini ortaya koymuştur.

Ultrasound imaging of the common carotid artery (CCA) is a non-invasive, accurate, cost-effective, and often portable medical imaging modality to visualize the characteristics of the carotid wall and lumen surfaces and quantify the severity of atherosclerosis. It is also used for border detection and texture characterization of atherosclerotic carotid plaques in the CCA that cause the artery to become narrowed and in-

Received: June 03, 2019 *Accepted:* August 23, 2019
Correspondence: Dr. Fereshteh Yousefi Rizi. No. 223, Headquarter of Islamic Azad University, South Tehran Branch, ZIP area 11, Azarshahr Street, North Iranshahr Street, Karimkhan-e-Zand Avenue, Tehran, Iran.
Tel: 00982188019250 e-mail: yousefi.f@gmail.com

crease the risk of stroke.[1] Although these medical images are widely used to detect narrowing or stenosis of the carotid artery, tracking rapid wall motion and vibration of the carotid artery for a better understanding of some pathologies and diagnosis remains problematic.[2,3]

Abbreviations:

CCA	*Common carotid artery*
FRUC	*Frame rate up-conversion*
LLE	*Locally linear embedding*
SSIM	*Structural similarity index*

Over the years, several techniques have been developed to increase the frame rate using different imaging applications. The simple method uses frame repetition and frame linear interpolation techniques, which are very easy to implement, but cause severe image quality degradation along the boundaries of objects in image sequences.[4] Konofagou et al.[5] and D'hooge et al.[6] increased the frame rate by reducing the view angle and decreasing the number of lines in a sector. The time needed to construct the whole image was reduced and the frame rate increased. Kanai et al.[7] used a sparse sector-scan format. They were able to obtain a high frame rate by reducing the number of ultrasound beams. However, the field of view was reduced, which is not suitable for full-view cardiac imaging. In addition, the lateral resolution was reduced proportionally to the number of lines. Steigner et al.[8] introduced an imaging technique based on electrocardiogram-gating and a retrospective multi-sector composite method to increase the frame rate. Hasegawa et al.[9] used parallel receive beamforming for the acquisition of ultrasonic radiofrequency echoes at a high frame rate. In their work, plane waves were transmitted only 3 times and created 24 beams for each transmit beam. The disadvantage of their proposed method is that lateral resolution in the B-mode image was reduced. Other approaches to increasing the frame rate are coded-excitation ultrasound imaging[10] and synthetic aperture ultrasound imaging.[11] However, these methods require complicated calculations.

In addition to these techniques, recently, methods for pseudo-increasing frame rate based on manifold learning have also been introduced.[12,13] Rizi et al.[12] applied manifold learning to specify a relationship between the ultrasound frames in the 2-dimensional (2D) space during consecutive cardiac cycles.

The currently proposed motion-compensated frame rate up-conversion (FRUC) method for carotid B-mode cine-loop sequence is based on a combination of manifold learning and optical flow techniques to accommodate carotid wall motion.

METHODS

Image acquisition

Carotid B-mode images of 54 healthy subjects of 2 genders and different ages were captured in 355 frames. All of the sequences had a frame rate of 60 frames/second. Depending on the subject's heart rate, these frames contain 6 to 8 cardiac cycles. Scanner settings should not be changed during the image acquisition. All of the subjects were positioned in the supine position with a head elevation of up to 45° and side tilt of 30° to the left and asked to rest for at least 10 minutes. B-mode images of the carotid walls were acquired in the longitudinal view for a total of 6 seconds. The subjects were asked to hold their breath and avoid swallowing. All the participants of the study read and signed forms of informed consent.

Proposed method

In recent years, there has been a great deal of interest in using the manifold learning method to pseudo-increase the frame rate of ultrasound images, but this method is dependent on the number of recorded cardiac cycles and frames.[12–14] A new hybrid method based on manifold learning and optical flow is proposed in this paper in order to increase the frame rate without the need for several cardiac cycles of carotid ultrasonography or the need for simultaneous electrocardiography to specify the exact cardiac phase of the frames, which was vital in the previously reported work based on manifold learning.[12,13] FRUC methods are generally categorized into 2 groups. First, there are interpolation-based methods that calculate the skipped frame along the temporal axis without considering the motion of the object. While simple, these methods result in jerkiness and blurriness of the boundaries of moving objects. The second group comprises motion-compensated frame interpolation methods, which provide more accuracy. The proposed hybrid method uses manifold learning to map the B-mode frames of 6 to 8 cardiac cycle into 2D space to find the neighbor and similar frames of different cycle and highly variant frames. In the next step, optical flow was applied to estimate the motion in 2 directions to create a new frame between the successive frames with a relatively great distance on the 2D map.

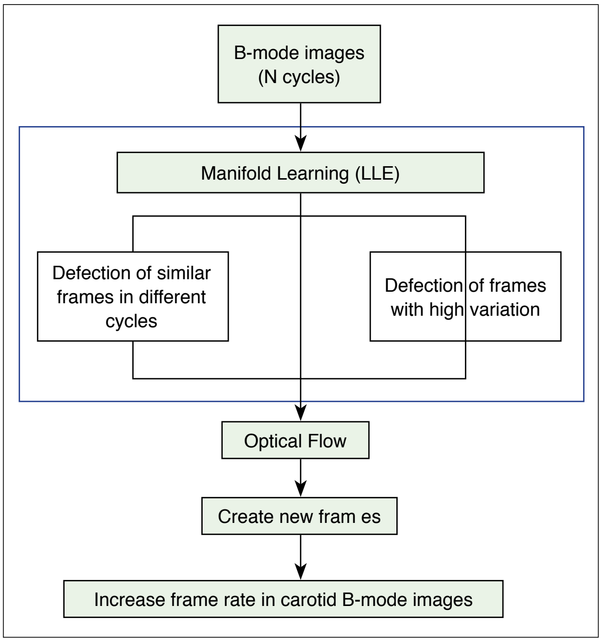

Figure 1. Block diagram of the proposed motion-compensated frame rate up-conversion method for carotid B-mode cine-loop sequence.

These steps are explained in the following sub-sections. The general idea of the proposed motion-compensated FRUC method is shown in Fig. 1.

Locally linear embedding

Manifold learning has become a popular approach to nonlinear dimensionality reduction in last decade.[15] These algorithms are based on the hypothesis that the dimensionality of many data sets is artificially high and that each sample can be described as a function of only a few underlying parameters. The algorithms are designed to uncover intrinsic parameters in order to find a low-dimensional representation of the data. In other words, the data points are actually samples from a high-dimensional manifold that is embedded in a low-dimensional space.[15,16] A large variety of manifold learning methods have been introduced, such as: isometric mapping (Isomap), locally linear embedding (LLE), Laplacian eigenmaps, and local tangent space alignment.[16–21] In this study, the LLE algorithm was applied due to the advantage that frames of the same cardiac phase in the high-dimensional space remain close together in the low-dimensional space. The LLE algorithm transforms n data samples (observations) of the X data set with dimensionality D into a new data set Y consisting of n points D-dimensional (where d < D and often d << D) while retaining the geometry of the data as much as possible:[19]

$$x_1.x_2.x_3.\dots.x_n \in R^D \rightarrow y_1.y_2.y_3.\dots.y_n \in R^d \qquad (1)$$

The embedding is optimized to preserve the local configurations of nearest neighboring images. LLE attempts to represent the manifold locally by reconstructing each input point as the weighted combination of its neighbors. The algorithm can be divided into 3 steps:[19,22]

1. Compute the neighbors of each data point. $\vec{X_\iota}$.

2. Compute the weights W_{ij} that best reconstruct each data point $\vec{X_\iota}$ from its neighbors, minimizing the cost in eq. (2) by constrained linear fits.

$$\varepsilon(w) = \sum_i \left| \vec{X_\iota} - \sum_j W_{ij}\vec{X_j} \right|^2 \qquad (2)$$

Compute the vectors $\vec{Y_\iota}$ best reconstructed by the weights W_{ij}, minimizing the quadratic form in Eq. (3) by its nonzero eigenvectors.

$$\Phi(Y) = \sum_i \left| \vec{Y_\iota} - \sum_j W_{ij}\vec{Y_j} \right|^2 \qquad (3)$$

Motion compensation using optical flow

As mentioned in the previous section, the main disadvantage of increasing the frame rate based on a manifold learning algorithm is the dependency of this technique on the number of heart cycles and the number of frames recorded. To overcome this limitation, an optical flow algorithm was applied to estimate the motion.[23,24] In general, the use of optical flow provides more accurate motion estimation and details of the target tissue (Fig. 2).

In the first step, we use a block-matching algorithm to determine integer pixel displacements $\overline{\Delta x}$ and $\overline{\Delta y}$. If $(\Delta x.\Delta y)$ is the true displacement, then $(\overline{\Delta x}.\overline{\Delta y})$ determined with the block-matching algorithm should be a good integer estimate of $(\Delta x.\Delta y)$. Once $(\overline{\Delta x}.\overline{\Delta y})$ is determined, the image block is shifted by $\overline{\Delta x}$ pixels along "x" direction and $\overline{\Delta y}$ pixels along "y" direction.

The second step of the algorithm is to use the Taylor series approximation to refine the search. Since the shifted image $f(x + \delta x.y + \delta y)$ differs from the true image by only $(\delta x.\delta y)$ where $|\delta x| < 1$ and $|\delta y| < 1$ the Taylor series approximation is approximately valid. The overall displacement can be determined as:[25]

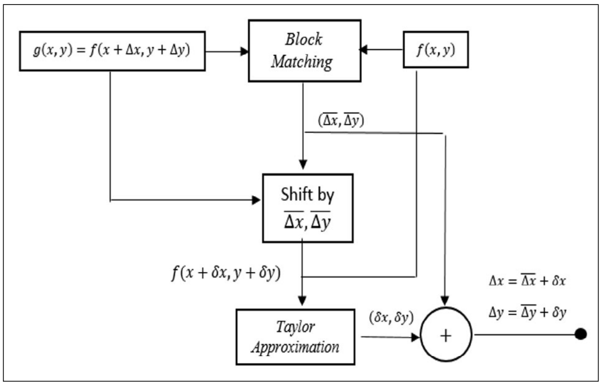

Figure 2. Block diagram of motion estimation using a combination of block-matching algorithms and the Taylor approximation (simplified optical flow).[25]

$$\Delta x = \overline{\Delta x} + \delta x \text{ and } \Delta y = \overline{\Delta y} + \delta y \quad (4)$$

If $f\,(x.y)$ and $g(x.y)$ are 2 consecutive frames in an image set, then the optical current is defined according to:(5)

$$g(x.y) = f(x + \Delta x.y + \Delta y) \approx f(x.y) + \Delta x \frac{\partial}{\partial x} f(x.y) + \Delta y \frac{\partial}{\partial y} f(x.y) \quad (5)$$

Finally, with the extraction of motion vectors, a new frame $\tilde{f}(x.y)$, can be placed between 2 successive frames $f\,(x.y)$, and $g(x.y)$.

Motion-compensated frame rate up-conversion

A new hybrid method based on manifold learning and optical flow is proposed in order to increase the frame rate without the need for simultaneous electrocardiography. To assess the dimension of the underlying structure in a sequence of carotid B-mode images, the LLE algorithm is applied[19,22] and each frame is projected to a point on the 2D space to extract the relationship between the mapped frames.[15,19,22] In other words, in this study, the LLE algorithm was applied on 2D carotid ultrasound images to determine the relationship between the frames of different cycles. With this approach, it is possible to detect similar frames in a different cycle and diagnose frames with high variations. By mapping frames into a lower-dimensional space, it is possible to distinguish frames with high variations. After the detection of similar frames in different cardiac cycles and the location of compensated frames, by applying the optical flow motion estimation algorithm, a motion-compensated frame was reconstructed. Since the carotid arterial wall moves due to blood flow during the cardiac pulse, the wall position is periodically changed in the radial and longitudinal direction. The carotid wall motion is not dominant, so the use of traditional motion estimation techniques, such as block-matching and optical flow have generally been reported in the literature.[19,15] After determining the location of the compensating frames, the proposed method is based on a combination of block-matching algorithms and the Taylor approximation (simplified optical flow),[23–25] and with the extraction of motion vectors, a new frame can be inserted between 2 initial, successive frames.

RESULTS

Carotid B-mode images are used as the input in the LLE algorithm. Each frame is a matrix with the resolution of 2526×129 pixels and the carotid area cropped first. The cropped images are reshaped to an array, so the dimension of the first space is high. The images are embedded in 2D space using the LLE algorithm. A plot of normalized eigenvalues shows that most of the information of a heart cycle in sequential B-mode images is represented in 2D, and thus, the LLE algorithm has mapped the B-mode images in a 2D space. A 2D map of the consecutive frames of a cardiac cycle is shown in Figure 3. The 3 dense areas on the manifold are related to different phases of the heart cycle. In each dense region, the corresponding B-mode frame is shown. The candidate high-variant consecutive frames can also be seen (red arrow).

As shown in Figure 3, the distance between consecutive frames 89 and 90 is high on a single heart cycle, which represents the high difference between the 2 consecutive frames related to each other and also the

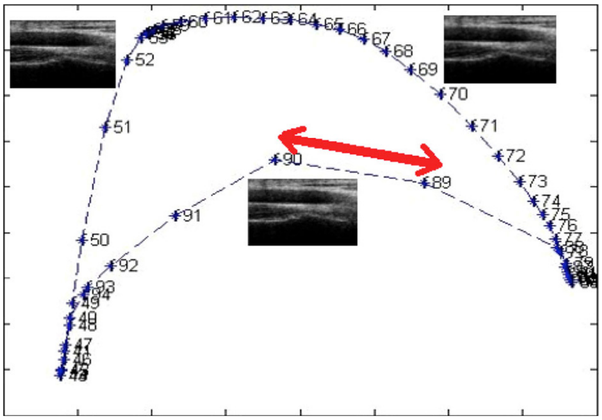

Figure 3. The 2-dimensional non-linear embedding of a cycle (55 frames), using locally linear embedding (k=12 neighbors).

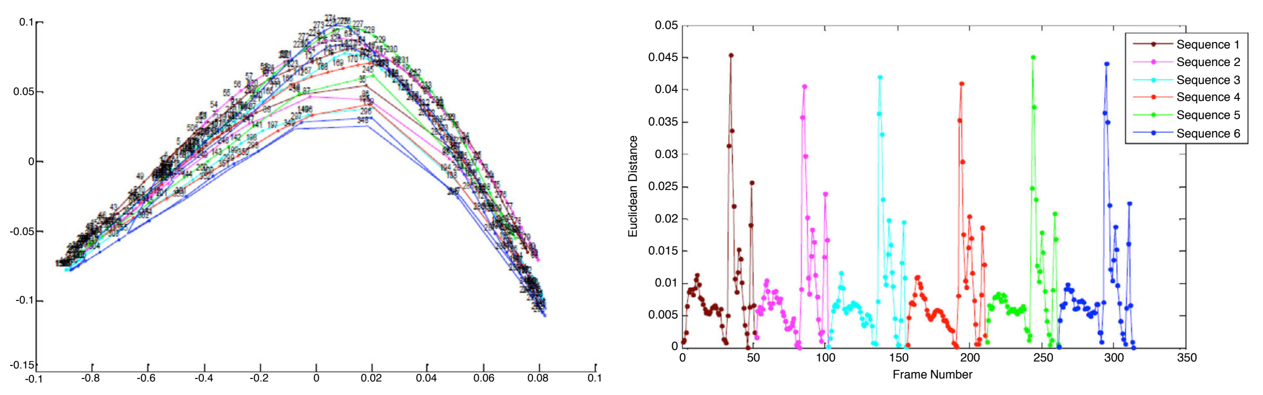

Figure 4. Two-dimensional non-linear embedding of 6 successive cycles with different colors for a subject using the locally linear embedding algorithm (k=12 neighbors) and its corresponding Euclidian distance diagrams.

loss of rapid movements and vibrations of the arterial wall between these 2 consecutive frames. The place to insert the "n" images is detected by considering these distance diagrams along with their manifolds.

In order to show the quantitative relationship between the points (corresponding to frames), the Euclidean distance between 2 successive points in the manifold of 5 cycles is also calculated (Fig. 4). Due to variations in carotid artery wall stiffness and wall motion in different ages and the dynamic nature of wall motion during a cardiac cycle, the corresponding manifolds are not similar. However, in all cases, the cyclical nature of the cardiac motion leads to a closed curve. It should be noted that due to differences in the heart rate of each case, the number of frames per cardiac cycle is not the same.

Table 1. Evaluation criteria

Evaluation criteria	LLE	OF	Motion compensated FRUC (LLE+ OF)
CORR	0.58	0.31	0.78
SSIM	0.45	0.15	0.97
Frame number ("*n*" cycle)	n	1	2^n

LLE: Locally linear embedding; OF: Optical flow; FRUC: Frame rate up-conversion; CORR: Correlation; SSIM: Structural similarity index.

Performance evaluation

The following strategy was used in order to evaluate the proposed method for motion-compensated FRUC:

1) Remove every other frame of the B-mode images of a cardiac cycle.

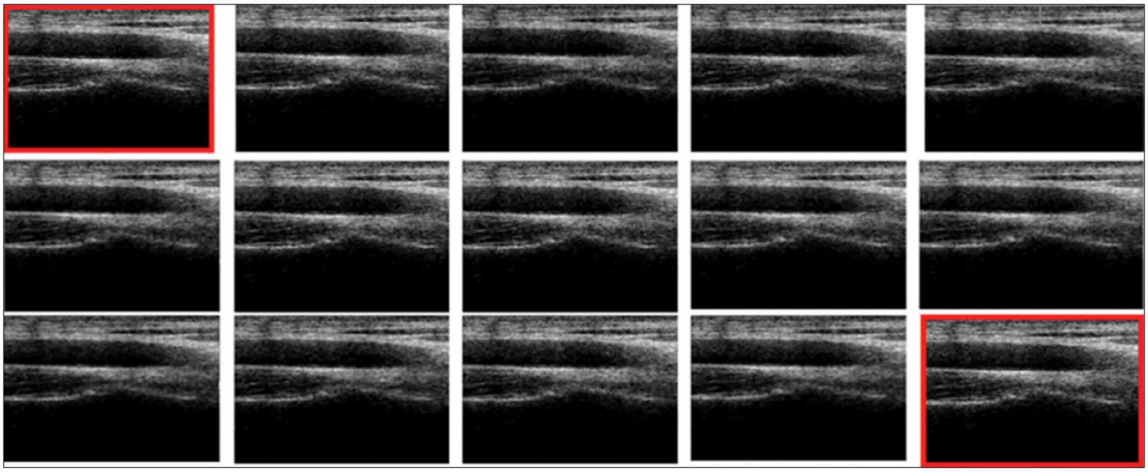

Figure 5. The results of applying the proposed method to increase the frame rate of ultrasound images of the carotid artery.

2) Generate new frames between every pair of consecutive frames using our proposed method.

3) Compare the resulting up-conversion frames with the original frame that was removed in step 1.

To compare the similarity between the original frames removed in the first step and the up-converted frames, several evaluation criteria were calculated, such as the structural similarity index (SSIM) and correlation, as well as the number of up-converted frames that can be generated, as shown in Table 1.

The average SSIM and correlation values for the cineloops of 54 subjects were calculated using the omitted frame and the frame generated using LLE, optical flow, and the proposed motion-compensated FRUC method. As seen in the results of Table 1, although increasing the frame rate in ultrasound images with manifold learning yields acceptable results, this method remains dependent the number of recorded cardiac cycles and frames. The proposed up-conversion method, which compensates for motion based on manifold learning and optical flow generated preferable results without the need for simultaneous electrocardiography. The evaluation of the results supports the conclusion that the proposed up-conversion method offers several advantages over manifold learning.

In order to evaluate the performance of the proposed method, the visual quality of the new inserted frames was evaluated and approved by an expert cardiologist (Fig. 5).

DISCUSSION

One of the most commonly used methods for evaluating carotid artery disease is ultrasound imaging, which can detect narrowing or stenosis of the carotid artery, a condition which substantially increases the risk of stroke. These medical images are widely used to assess the severity of atherosclerosis and its progression; however, tracking the rapid motions and vibrations of the carotid artery wall for better interpretation of medical images and a more thorough diagnosis is still a challenging issue. Increasing the frame rate of carotid ultrasound images should assist with a better understanding of some pathologies and enhance diagnostic capabilities.

In this paper, we proposed a new motion-compensated up-conversion method based on manifold learning and optical flow in order to increase the frame rate in noninvasive carotid ultrasonography. The LLE algorithm was applied on 2D carotid ultrasound images to determine the relationship between the frames of different cycles. Using this approach, it was possible to define similar frames in a different cycle and also to diagnose frames with high levels of variation. After the detection of similar frames in different cardiac cycles and establishing compensating frames, a motion-compensated frame was reconstructed by applying the optical flow motion estimation algorithm.

As a result, an informative cycle with more frames was created that can provide a more accurate consideration of carotid wall motion and vibration compared with the typical ultrasound systems. The proposed hybrid method outperformed the manifold learning approach in terms of the frame rate and SSIM.

Conclusion

In this paper, a motion-compensated FRUC method is proposed for carotid artery cineloop images. Using the manifold of the embedded points, the corresponding B-mode images from different cardiac cycles that were candidates to be high variants were identified and intermediate frames between the initial successive frames were calculated using optical flow. This hybrid FRUC method that compensates for motion in the artery outperforms previously proposed pseudo-increasing frame rate approaches based on manifold learning.

Peer-review: Externally peer-reviewed.

Conflict-of-interest: None.

Authorship contributions: Concept: F.Y.R.; Design: S.N., F.Y.R.; Supervision: F.Y.R., Z.A.S.; Materials: Z.A.S.; Data: Z.A.S.; Analysis: S.N.; Literature search: F.Y.R., S.N.; Writing: S.N.; Critical revision: F.Y.R., S.N.

REFERENCES

1. Gamble G, Zorn J, Sanders G, MacMahon S, Sharpe N. Estimation of arterial stiffness, compliance, and distensibility from M-mode ultrasound measurements of the common carotid artery. Stroke 1994;25:11–6.
2. Ciccone MM, Scicchitano P, Zito A, Agati L, Gesualdo M, Mandolesi S, Correlation between coronary artery disease severity, left ventricular mass index and carotid intima media thickness, assessed by radio-frequencyCardiovasc Ultrasound 2011;9:32.
3. Heiss G, Sharrett AR, Barnes R, Chambless LE, Szklo M,

Alzola C. Carotid atherosclerosis measured by B-mode ultrasound in populations: associations with cardiovascular risk factors in the ARIC study. Am J Epidemiol 1991;134:250–6.

4. K. Ravi, R. Hazra, A Kasai. Method and apparatus for increasing video frame rate. 2001. Available at: https://patents.google.com/patent/WO1999057906A1. Accessed Oct 23, 2019.
5. Wang S, Lee W, Luo J, Konofagou EE. A composite imaging technique for high frame-rate and full-view cardiovascular ultrasound and elasticity imaging. IEEE Ultrason Symp. Accessed Oct 23-31, 2007.
6. Konofagou EE, D'hooge J, Ophir J. Myocardial elastography-a feasibility study in vivo. Ultrasound Med Biol 2002;28:475–82.
7. Kanai H, Sato M, Koiwa Y, Chubachi N. Transcutaneous measurement and spectrum analysis of heart wall vibrations. Ultrasonics, Ferroelectrics and Frequency Control, IEEE Trans 1996;43:791–810.
8. Steigner ML, Mitsouras D, Whitmore AG, Otero HJ, Wang C, Buckley O, et al. Lodinated contrast opacification gradients in normal coronary arteries imaged with prospectively ECG-gated single heart beat 320-detector row computed tomography. Circ Cardiovasc Imaging 2010;3:179–86.
9. Hasegawa H, Kanai H. Improving accuracy in estimation of artery-wall displacement by referring to center frequency of RF echo. IEEE Trans Ultrason Ferroelectr Freq Control 2006;53:52–63.
10. Misaridis T, Jensen JA. Use of modulated excitation signals in medical ultrasound. Part II: Design and performance for medical imaging applications. IEEE Trans Ultrason Ferroelectr Freq Control 2005;52:192–207.
11. Jensen JA, Nikolov, S, Gammelmark KL, Pedersen MH. Synthetic Aperture Ultrasound Imaging. Ultrasonics 2006;44:e5–e15.
12. Rizi FY, Setarehdan K, Behnam H. Pseudo-increasing Frame Rates of Carotid Artery B-mode Images using Manifold Learning. Available at: file:///Users/batti/Downloads/Pseudo-increasing.pdf. Accessed Dec 18-20, 2013.
13. Gifani P, Behnam H, Sani ZA. A New Method for Pseudo-increasing Frame Rates of Echocardiography Images Using Manifold Learning. J Med Signals Sens 2011;1:107–12.
14. Wu H, Huynh TT, Souvenir R. Echocardiogram enhancement using supervised manifold denoising. Med İmage Anal 2015;24:41–51.
15. Liang M, Breitkopf P, Quilliec G, Raghavan B, Villon P. Nonlinear shape-manifold learning approach: concepts, tools and applications. Archives of Computational Methods in Engineering 2018;25:1–21.
16. Hajizade R, Aghagolzade A, Ezoji M. Manifold Learning based on the Manifold Graph Construction using Sparse Representation. Journal of Iranian Association of Electrical and Electronics Engineers 2018;15:81–95.
17. Souvenir S, Pless R. Isomap and Nonparametric Models of Image Deformation. Washington, IEEE Computer Society; 2005. p. 195–200.
18. Libert L, D'Ambrosio C. The Isomap algorithm in distance geometry. Available at: https://pdfs.semanticscholar.org/35d6/de1e4e2bb1034278724b684843df1f3e19d9.pdf?_ga=2.76017618.674613872.1571834749-968797912.1547817018. Accessed Oct 23, 2019.
19. Ping H, Jing T, Xu X, Zhang L, Liao Z, Fan B. Advances in Computer Communication and Computational Sciences. In: Nonlinear Manifold Classification Based on LLE. Singapore: Springer; 2018. p.227–34.
20. Liu F, Zhang W, Gu S. Local linear Laplacian Eigenmaps: a direct extension of LLE. Pattern Recognition Letters . Amsterdam: Elsevier; 2016. p. 30–5.
21. Qian W, Wang W, Nian R, Shen Y, Björk KM, Lendasse A. Manifold learning in local tangent space via extreme learning machine. Neurocomputing 2016;174:18–30.
22. Bai L. Image Feature Dimension Reduction Based on Improved LLE Algorithm. "International Journal of Simulation 2015;16:1–8.
23. Golemati S, Sassano A, Lever MJ, Bharath AA, Dhanjil S, Nicolaides AN. Carotid artery wall motion estimated from B-mode ultrasound using region tracking and block matching. Ultrasound Med Biol 2003;29:387–99.
24. Denis F, Bouthemy P, Kervrann C. Optical flow modeling and computation: a survey. Computer Vision and Image Understanding 2015;134:1–21.
25. Chan SH, T vö D, Q. Nguyen T. Subpixel motion estimation without interpolation. IEEE International Conference on Acoustics Speech and Signal Processing (ICASSP). Accessed March 2010.

Keywords: Algorithm; carotid B-mode images; frame rate; locally linear embedding; manifold learning; motion-compensated; optical flow; up-conversion.

Anahtar sözcükler: Algoritma; karotis B-mod görüntüleri; kare hızı; yerel doğrusal gömme; manifold öğrenme; hareketle kompanse edilmiş; optik akış; yukarı dönüşüm.